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ALMA Memo 432

26 August 2002

# A Split-Block Waveguide Directional Coupler

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**ABSTRACT**

A simple waveguide directional coupler is described which uses the split-block type of construction common in millimeter-wave components. The coupler uses an array of metal probes suspended on quartz stand-offs. Depending on the number of coupling elements, the coupling can be in the range 15-30 dB, with typically ± 2 dB variation across the waveguide band, and directivity > 10 dB. The coupler, intended for injecting local oscillator power into a waveguide mixer, can be scaled for operation in any waveguide band.

**Keywords:** Directional couplers, Waveguide couplers, Millimeter wave directional couplers, Millimeter wave circuits.

## 1. INTRODUCTION

Of the many types of waveguide directional coupler, few are well suited to the E-plane split-block type of construction frequently used at millimeter wavelengths. Split-block branch-line couplers with strong coupling (e.g., 3 dB) are easily made [1] but when weak coupling is needed the narrow branch waveguides become difficult to machine and very precise alignment of the block halves is necessary. For example, the branch-line LO injection couplers used on the 230 GHz receivers at the Kitt Peak12-m telescope have two branch lines 0.0018" wide x 0.0185" deep in each half of the split block, and these must be well aligned when the two parts are assembled [2]. The split-block couplers described in this report, as shown in Fig. 1, use multiple small coupling probes suspended on quartz standoffs between full-height waveguides to obtain between 15 and 30 dB coupling depending on the number of probes. Machining is straight forward and alignment between block halves and positioning of the probes are not critical.

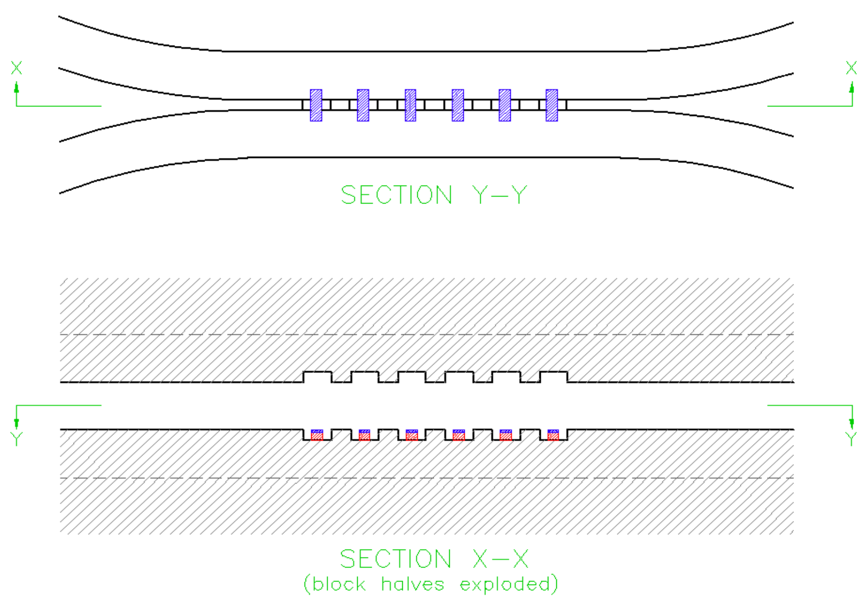


**Fig. 1. Diagram of the split-block coupler with six coupling probes (blue) on quartz standoffs (red). In the lower view, the two block halves are shown separated for clarity.**

The directional couplers described here were developed as LO couplers for use with the ALMA Band-6 SIS mixers (211-275 GHz). For reasons of reliability, cost, and size, it is desirable to integrate the LO coupler into the split-block SIS mixer. The design uses identical coupling probes which maximizes the coupling for a given number of probes but results in a lower directivity than would be obtained with a longer, tapered, coupling array.

Initially, it was hoped that the coupling probes for Band 6 could be fabricated on a thin dielectric substrate such as 0.003" Cuflon ($\varepsilon_r = 2.1$), but accurate control of the conductor and substrate dimensions appear to be impractical on a soft substrate. Probes on fused quartz substrates ($\varepsilon_r = 3.8$), with the substrate extending the full length of the probe, were investigated but found to result in substantial coupling variation across the band unless the quartz was very thin (~ 0.001" for Band 6). The most practical approach appears to be to support the metal coupling probes on small fused quartz standoffs. The probes can be fabricated in quantity by chemical milling or electroforming at a cost of a few cents each, and the quartz standoffs are made using a dicing saw, likewise at low cost. During assembly, the quartz standoffs are mounted in their slots using Armstrong A12 epoxy adhesive, then the metal probes are attached to the standoffs using the same adhesive.

## 2. WR-10 COUPLER

To enable a comparison to be made between simulated and measured results, a coupler was designed for the WR-10 band (75-110 GHz) using the FDTD EM simulator QuickWave. The dimensions are given in Fig. 2.

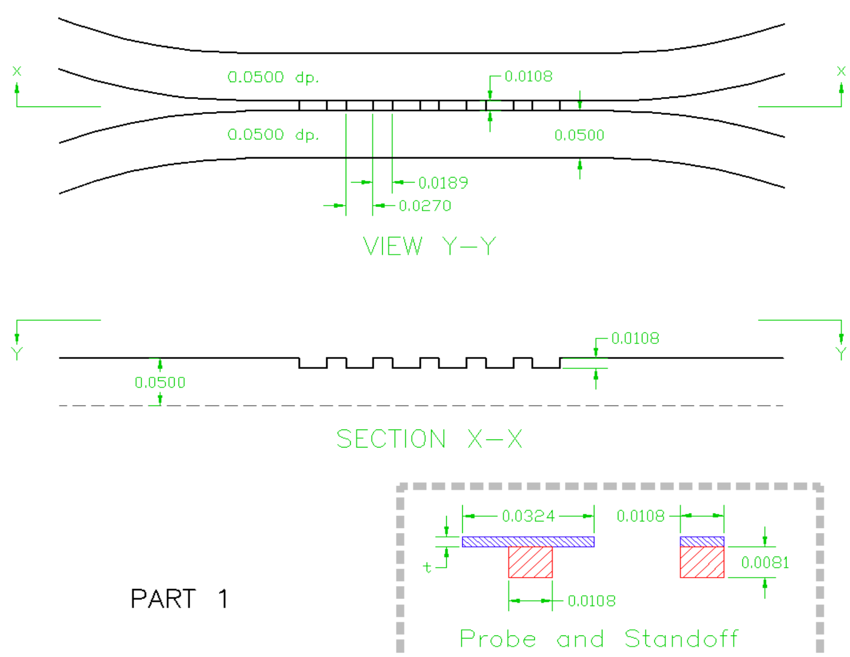


**Fig. 2. Dimensions of the WR-10 split-block coupler. Only the lower half-block is shown; the upper half is the mirror image. The box gives details of the probes (blue) and quartz standoffs (red). Dimensions are in inches. For the couplers tested below, the probe thickness t = 0.0016".**

Test couplers with four and six probes were constructed and measured using an HP8510 VNA. The measured results are shown in Figs. 3 and 5, and the results of the QuickWave simulation in Fig. 4 and 6.

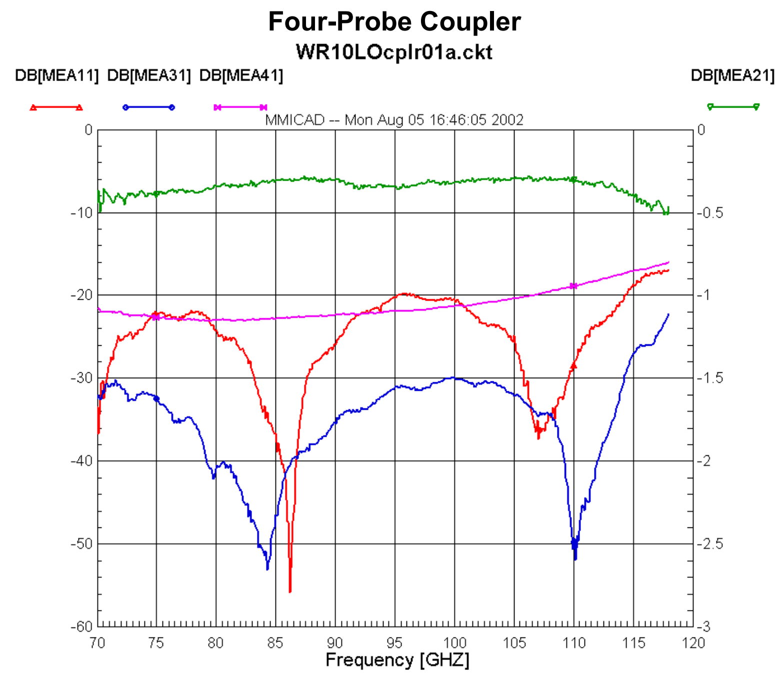


**Fig. 3. Measured S-parameters of the WR-10 directional coupler with four probes. Left scale: —— S11 dB, —— S31 dB, —— S41 dB. Right scale: —— S21 dB. (The WR-10 band is indicated by the markers at 75 and 110 GHz.)**

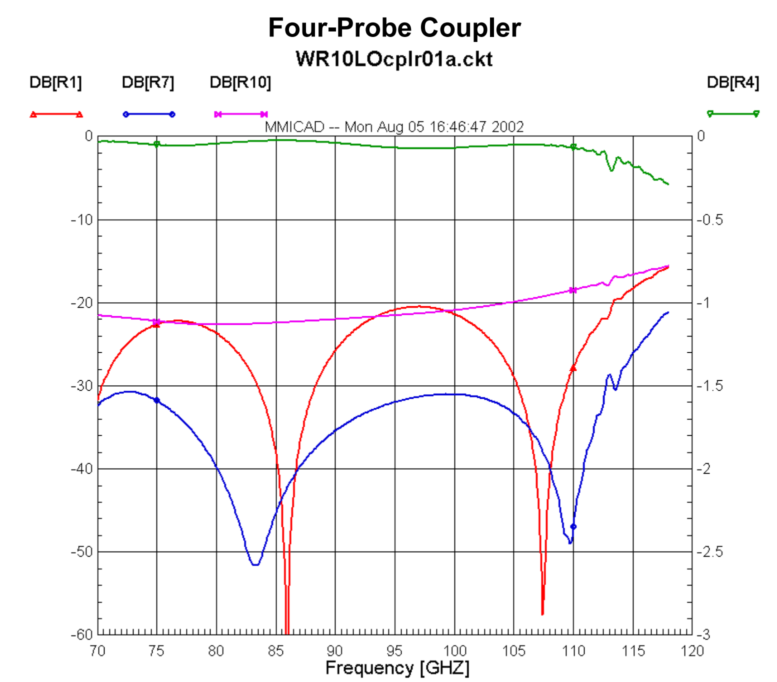


**Fig. 4. Results of the QuickWave simulation of the four-probe coupler. Left scale: —— S11 dB, —— S31 dB, —— S41 dB. Right scale: —— S21 dB. (The WR-10 band is indicated by the markers at 75 and 110 GHz.)**

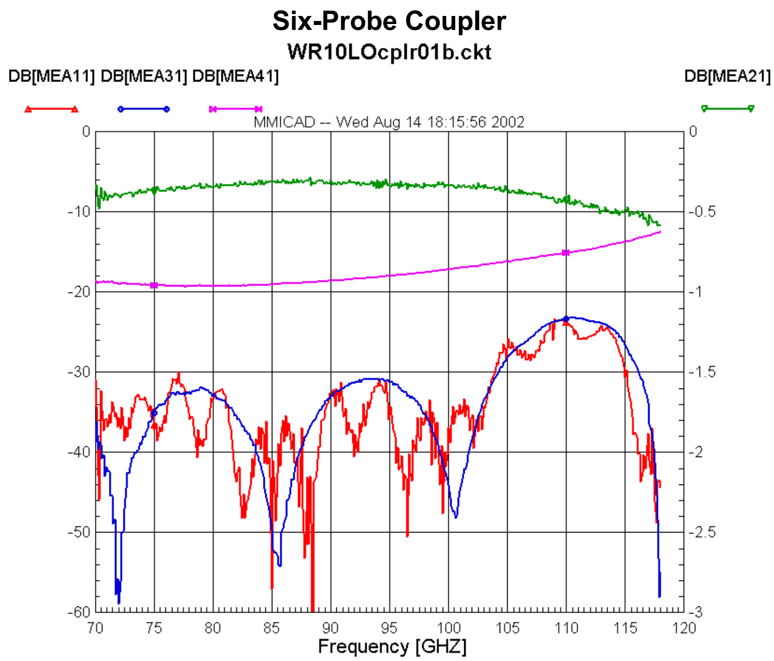


Fig. 5. Measured S-parameters of the WR-10 directional coupler with six probes. Left scale: —— S11 dB, —— S31 dB, —— S41 dB. Right scale: —— S21 dB. (The WR-10 band is indicated by the markers at 75 and 110 GHz.)

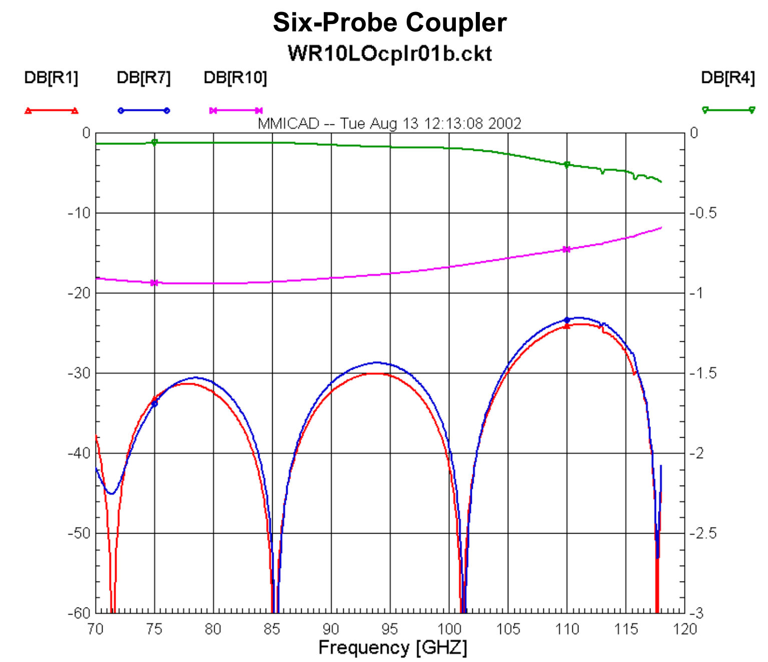


Fig. 6. Results of the QuickWave simulation of the six-probe coupler. Left scale: —— S11 dB, —— S31 dB, —— S41 dB. Right scale: —— S21 dB. (The WR-10 band is indicated by the markers at 75 and 110 GHz.)

To test the effect of imperfect probe positioning, the four-probe coupler was simulated with all the probes moved down 0.002" so they extend 0.004" further into the lower waveguide than into the upper waveguide. The result is shown in Fig. 7, which indicates little change in coupling compared with Fig. 4.

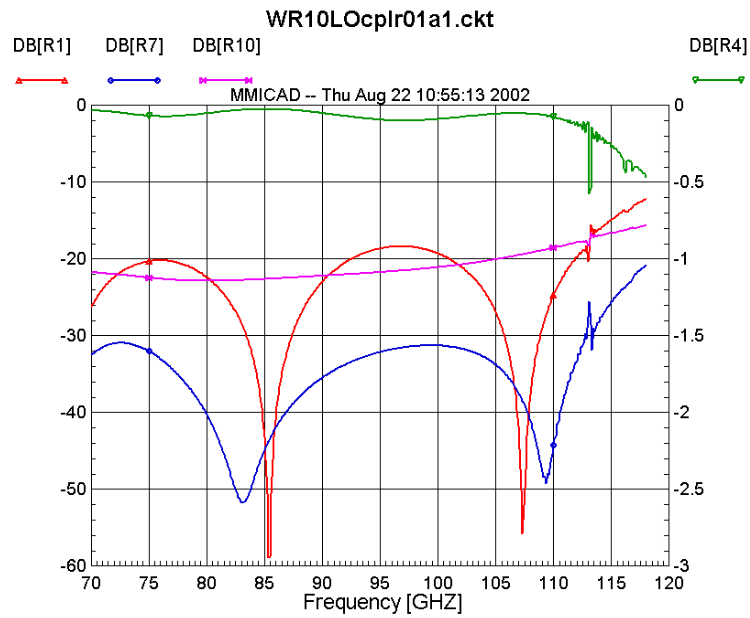


**Fig. 7. Results of the QuickWave simulation of the four-probe coupler with all probes moved down 0.002". (Compare with Fig. 4.) Left scale: —— S11 dB, —— S31 dB, —— S41 dB. Right scale: —— S21 dB. (The WR-10 band is indicated by the markers at 75 and 110 GHz.)**

The effect of the coupling probe length is demonstrated by increasing the probe lengths 0.004" (0.002" in each waveguide). The result is shown in Fig. 8, which indicates a greater variation of coupling with frequency compared with Fig. 4.

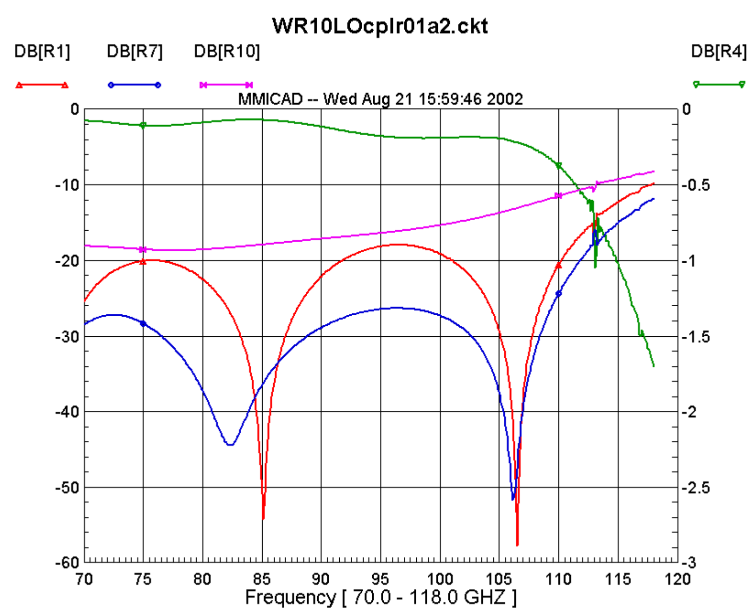


**Fig. 8. Results of the QuickWave simulation of the four-probe coupler with all probes increased in length by 0.004". (Compare with Fig. 4.) Left scale: —— S11 dB, —— S31 dB, —— S41 dB. Right scale: —— S21 dB. (The WR-10 band is indicated by the markers at 75 and 110 GHz.)**

Increasing the probe thickness from 0.0016" to 0.0032" increases the coupling by ~ 2 db across the band, as shown in Fig. 9.

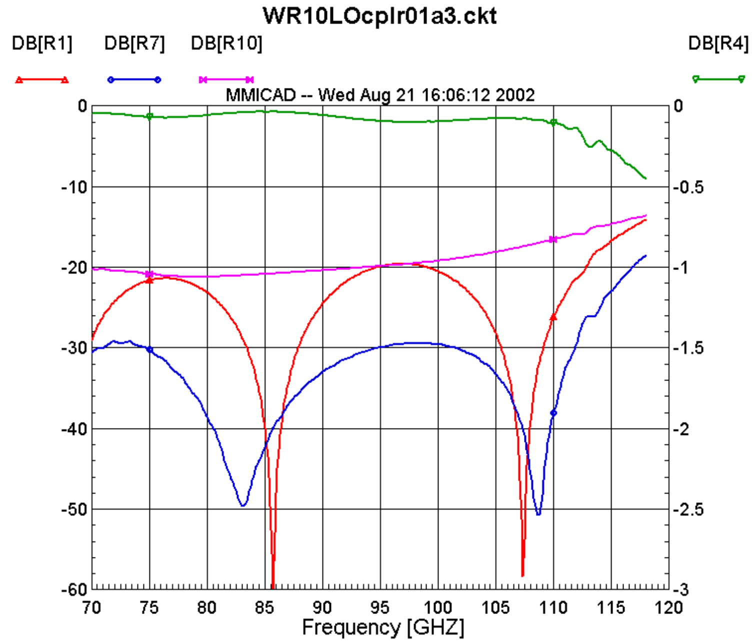


**Fig. 9. Results of the QuickWave simulation of the four-probe coupler with the thickness of all probes increased from 0.0016" to 0.0032". (Compare with Fig. 4.) Left scale: —— S11 dB, —— S31 dB, —— S41 dB. Right scale: —— S21 dB. (The WR-10 band is indicated by the markers at 75 and 110 GHz.)**

## 3. DISCUSSION

The measurements with the VNA (Figs. 3 and 5) agree well with the QuickWave simulations (Figs. 4 and 6). As expected, the (power) coupling is approximately proportional to the square of the number of probes. Alignment of the probes is not highly critical, as illustrated in Fig. 7; the main effect of having the probes protruding further into one waveguide than the other is to increase the SWR in the first waveguide while reducing it in the other, but the coupling is not substantially affected. Increasing the overall probe length increases the coupling but also increases the coupling variation with frequency (Fig. 8); if stronger coupling is needed it is therefore preferable to use additional probes rather than longer ones, and thicker probes can also be used. Probe thickness is not critical; doubling the probe thickness increased the coupling by ~ 2 dB (Fig. 9).

The directivity of the coupler (|S41|/|S31|) is not high, > 10 dB for the four-probe design, improving with the number of probes. The low directivity is a consequence of the small number of probes and of using identical probes in each location. A coupler with a larger number of shorter probes would have better directivity for the same coupling. If the array were tapered at its ends, the directivity could be further improved. For the present application, LO injection, the shorter designs with identical probes as described here are acceptable and have the advantages of compactness and simplicity.

The small spikes in the simulated frequency characteristics just above the nominal waveguide band (most clearly seen at ~ 113 GHz in Fig. 7) are the result of a trapped mode resonance in the vicinity of the coupling probes. In WR–10 waveguide, the $TE_{01}$ mode is cutoff below $2f_C$ = 118 GHz ($f_C$ is the cutoff frequency of the fundamental $TE_{10}$ mode). In the coupler, the probe channels modify the waveguide boundary conditions so the cutoff frequency of the $TE_{01}$ mode is lowered, and in a narrow band of frequencies just below $2f_C$ the $TE_{01}$ mode can propagate in the coupling region but is trapped by the normal waveguides on either side. This results in a $TE_{01}$-mode resonant cavity. Fig. 9 shows the z-directed E-field component in the coupler after the propagating modes have died away. The $TE_{01}$ mode is visible in the coupling region with the fields decaying rapidly in the normal waveguides. The slight asymmetry caused by the quartz standoffs allows weak coupling between the normal $TE_{10}$ mode and the trapped $TE_{01}$ mode, so the resonance is visible in the coupler characteristics. The absence of these spikes from the VNA measurements is attributed to damping out of the resonance by the waveguide loss (assumed negligible in the simulations). In cryogenic applications, it is possible that substantially reduced waveguide loss at low temperature would reveal the resonance, so care should be taken in any modification of this design to ensure that the resonance remains above the waveguide band.

The directional coupler described here can be scaled for operation in any waveguide band.

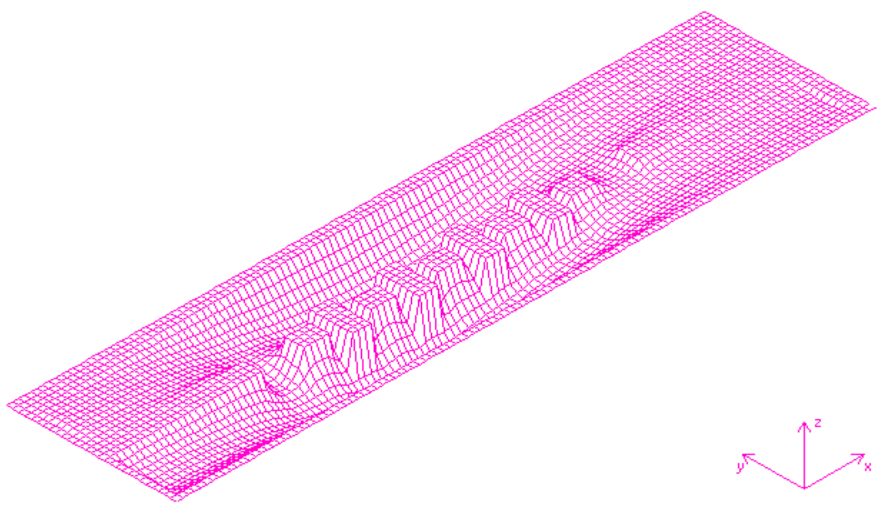


**Fig. 9. QuickWave simulation of the electric field component $E_Z$ in the four-probe coupler after the propagating components have died away. This trapped mode is weakly coupled to the dominant modes in the two waveguides and accounts for the small spikes seen just above the nominal waveguide band in the frequency characteristics of the coupler.**

## 4. REFERENCES


[1] S. Srikanth and A. R. Kerr, “Waveguide Quadrature Hybrids for ALMA Receivers,” ALMA Memo 343, 11 Jan 2001. http://www.alma.nrao.edu/memos/.

[2] A. R. Kerr, National Radio Astronomy Observatory, 1992.